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NO. 12959

U.S. ARMY TACOM

INITIAL DESIGN AND STRESS ANALYSIS OF A COMPOSITE (FRP) ROADWHEEL FOR THE M1 ABRAMS MAIN BATTLE TANK

(INTERIM TECHNICAL REPORT)

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A Composite roadwheel for the US Army M1 Abrams Main Battle Tank has been designed for volume production.

The composite roadwheel uses an E-glass/epoxy advanced composite material, produced by wet filament-winding followed by compression molding at a high temperature to compact and cure the matrix. Aluminum inserts are used to resist corrosion and creep at the bolted interfaces between the component and the vehicle. (Cont'd)

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Stress analysis using NASTRAN finite-element computer models, combined with validation tests on an aluminum roadwheel, have been used to establish the strength of the existing aluminum wheel, and to evolve a composite wheel of comparable strength.

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1.0. INTRODUCTION

Compositek Engineering Corporation, a subsidiary of the Kelsey-Hayes Company, was awarded Contract No. DAAE07-83-R082 in August of 1983 by the US Army Tank Automotive Command. The contract involves design and automated-process development for fiber-reinforced plastic (FRP) composite roadwheels for the M1 Abrams Main Battle Tank.

The production approach to be adopted for the composite wheels involves high-speed filament-winding, using continuous fibers in a resin matrix. This produces a complex structure with fibers oriented in the directions of the principal loads. Complex 3-dimensional structures of this type cannot reasonably be analyzed by conventional techniques, so computer-based finite-element technqiues must be used.

This report describes the design work and finite-element analysis carried out on the composite roadwheel, and outlines the analysis carried out on the existing aluminum roadwheel to validate the computing techniques and establish baseline loads. Finally, a program of tests to verify the integrity of the composite wheel process and design is outlined.

2.0. OBJECTIVE

The primary objective was to design a composite roadwheel and associated manufacturing process suitable for economic production in relatively large (30,000/year) quantities. To validate the design of the wheels produced, a stress analysis was to be done using finite-element techniques, and a testing program was undertaken.

3.0. CONCLUSIONS

The design and manufacturing process for the composite roadwheel has been adequately defined, and a test requirement based on the properties of the existing aluminum wheel has been specified.

The maximum allowable radial load for the aluminum wheel is 68,000 lbs. (302.5 kN) and the allowable radial fatigue load, 33,000 lbs. (146.8 kN). The composite wheel is adequate to withstand these loads. A program of maximum and fatigue load testing for composite wheel has been specified, and submitted for approval.

4.0. RECOMMENDATIONS

Tooling for fabrication of representative components should be procured.

5.0. DISCUSSION

5.1. Design Approach

5.1.1. General Considerations. The general approach is based on the concept of filament-wound preforms and compression molding, using hard tooling mounted in a 300-ton capacity hydraulic press. This approach was chosen to combine speed of manufacture, low technical risk, and minimum cost, for both prototype and production units.

The use of filament-wound preform construction allows the filaments to be oriented to give a composite with optimum properties in the directions of loading. In the case of the roadwheel, the major loadings are radial and lateral. These loads are best reacted to by a combination of radial fibers in the wheel disk area, and hoop fibers in the rim area.

Composite materials often exhibit long-term creep behavior, which may lead to loss of torque in bolted joints. This problem can be avoided by using metallic inserts around fastener holes. When graphite is used as a reinforcing material, these inserts must be of stainless steel to reduce galvanic corrosion effects. When glass is used, however, this galvanic action does not occur, and aluminum may be used for the inserts.

5.1.2. Manufacturing Sequence and Process. The technique adopted for production of the oriented composite is based on using filament-wound preforms. The preforms are obtained by winding filamentary materials impregnated with resin onto suitably-shaped mandrels.

Two types of filament orientation are needed for the roadhweel:

a. Quasi-radial fibers in the disk area

b. Hoop and quasi-radial fibers in the rim area

The quasi-radial fibers in both areas are approximated by using a "polar-winding" technique, using a special-purpose machine, purchased in support of this contract (Figure 5-1). The required mandrel represents two roadwheel profiles placed back-to-back, so preforms for two wheels are produced in each winding operation. An outer layer of circumferential (hoop) fibers is wound over the polar fibers to achieve the finished wheel outer profile and the two wheel preforms are separated by slitting before they are cured by compression molding. To give additional strength at the free edge of the wheel rim, a stiffening ring of hoop-wound fibers is produced by separately and bonded the inner surface of the rim in a secondary operation. The operations involved in manufacturing the composite parts of the roadhweel are illustrated in Figure 5-2.

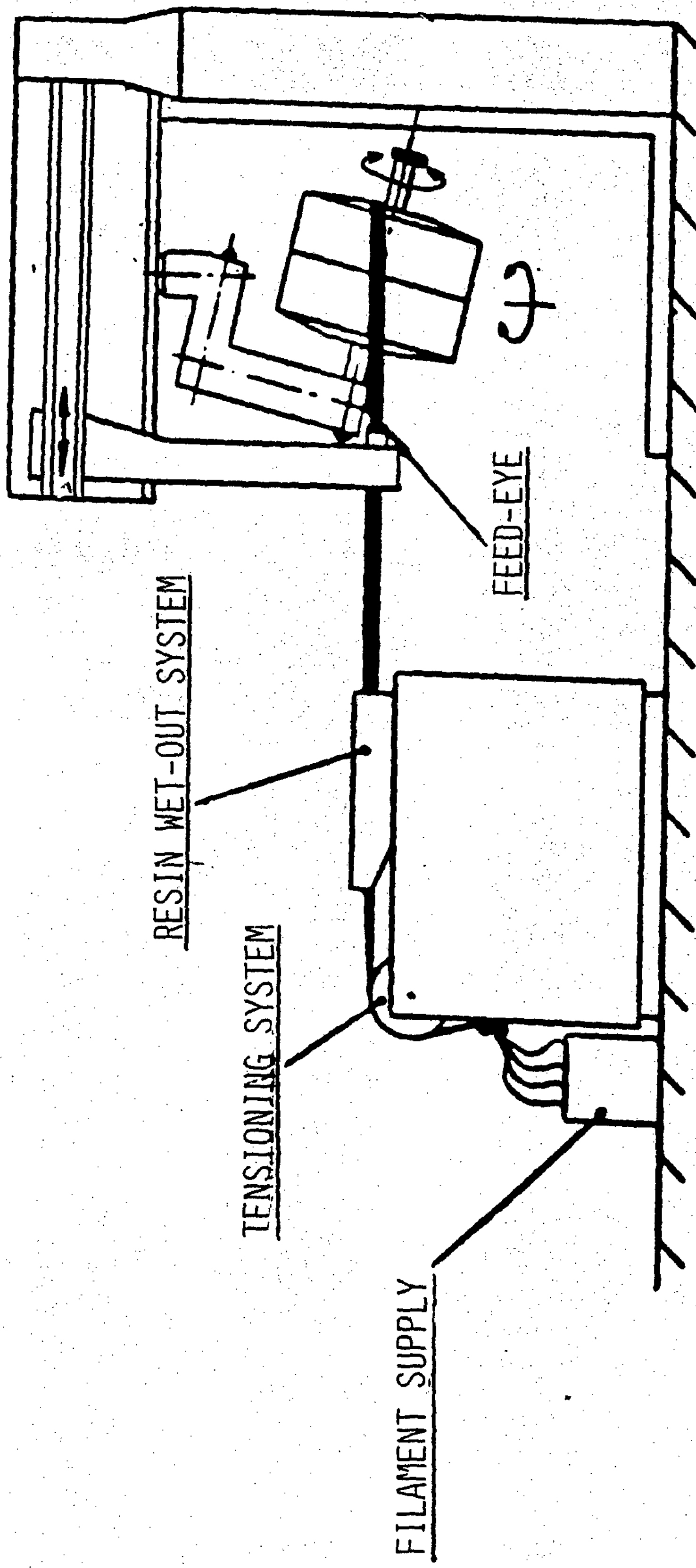

FIGURE 5-1: POLAR WINDING MACHINE

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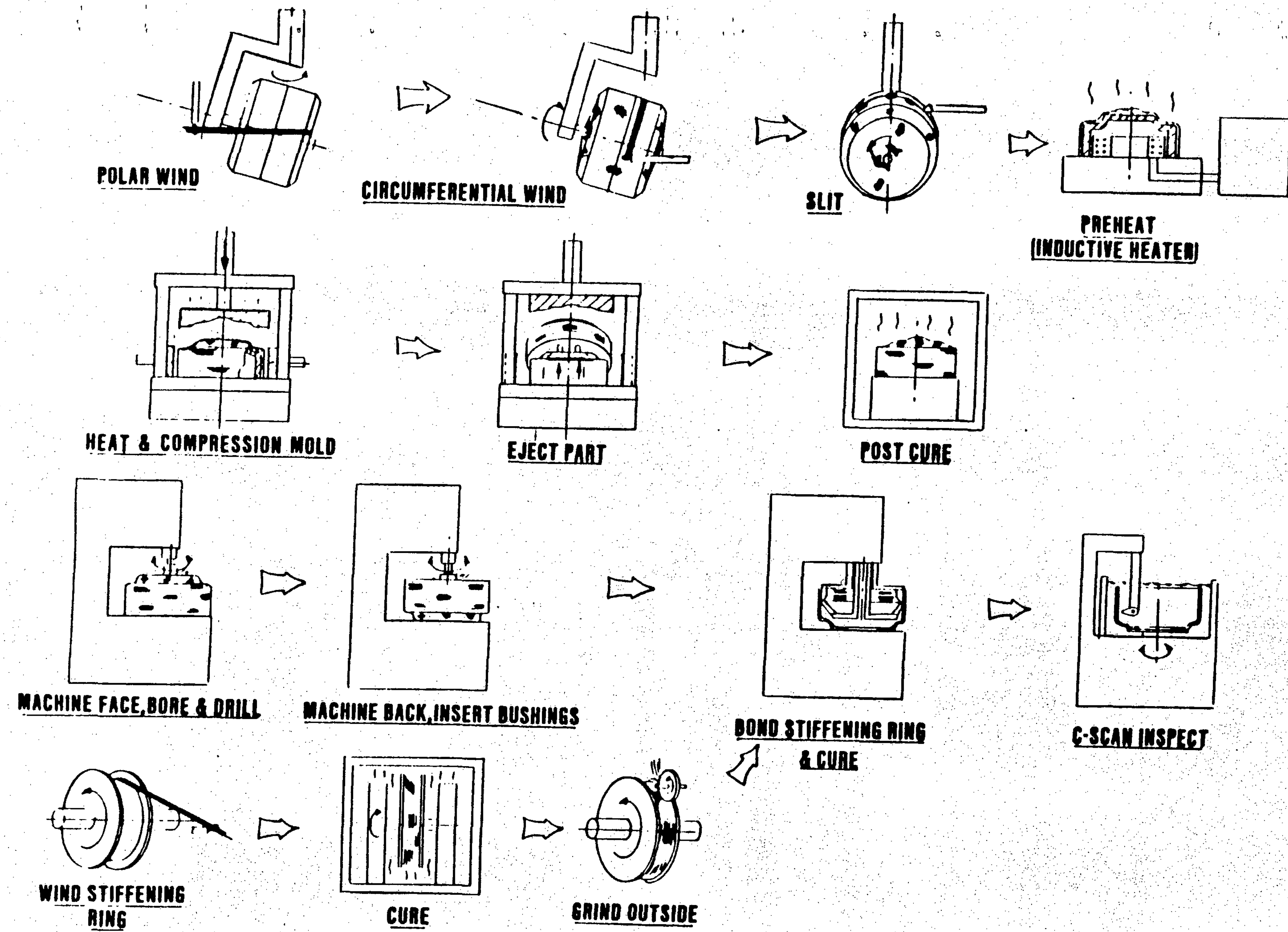

FIGURE 5-2: MANUFACTURING PROCESS

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Molding of the wheels is achieved without removing the preform from the mandrel, so the mandrel forms the male part of the mold. The mandrel and preform are transferred to a compression mold mounted in a 300-ton molding press. The mold is maintained at 350 degrees F (177 degrees C). De-bulking and preliminary cure of the roadwheel is achieved by closing the mold under pressure for 3-6 minutes. The wheel is then removed from the press, the stiffening ring is bonded in place, and the completed wheel is post-cured in an oven for 10-15 minutes to achieve full resin matrix strength. Compression molding was chosen over other potential consolidation techniques such as vacuum-bagging and autoclaving because of the high compaction pressures and high order of repeatability it offers.

Production of the roadwheel is completed by machining off excess material in the hub area, machining the required holes, and bonding in place the required inserts. Following completion of the composite parts of the wheel, a rubber tire is vulcanized in place using the same techniques used for the aluminum wheel.

5.1.3. Profile Generation and Fiber Orientation. The interface dimensions for the composite roadwheel profile are thickness, diameter at the hub, and diameter at the rim. Early in the program, the design goal was to duplicate the thickness of the existing aluminum design at these points, so that the composite part could be assembled using the same fasteners as the aluminum part. A further constraint was set, based on simple manual calculations, that there should be approximately equal thicknesses of radial and hoop material in the rim, to give a total thickness of around 0.5 in (12.7 mm).

Filament-winding is essentially a constant-volume process, so the variation of thickness and angle bears a fixed relatinship to the radius of winding. Based on theoretical calculations, a profile for the polar winding was generated (Figure 5-3). The predicted polar preform thickness varied from .25-in (6.35 mm) at the rim to .50 in (12.7 mm) at the center. The fiber angles (relative to a true radial orientation) varied from $\pm$ 15 degrees at the rim to $\pm$ 37 degrees at the center. Preliminary analysis of this wheel design showed excessive shear stresses at the rim/disk transition. The profile and winding angle (See Figure 5-4) for the preform were changed to give greater thickness in the transition area, and slightly higher fiber angles. The fiber angles on the revised profile vary from $\pm$ 25 degrees at the rim to $\pm$ 80 degrees at the hub. This change also reduces the amount of excess material which must be machined off the finished wheel.

5.1.4. Composite Material Choice. As mentioned previously, E-glass/epoxy was viewed as the composite system of choice. E-glass has an overwhelming cost advantage compared with other candidate filamentary reinforcements such as S-glass or graphite. Epoxy resins give good compromise between temperature capability, toughness, cost, and ease of processing.

The glass material provisionally selected is Owens Corning Type 30,432 E-glass, although equivalent products are available from other suppliers. Mechanical property testing was carried out on a number of candidate epoxy resins, including products from Shell, Furane and Celanese. All the resins were judged suitable for the roadhweel program. The Celanese resin was provisionally selected on the basis of favorable company experience with it on a similar program, to produce a composite sproket carrier for the U.S. Marine Corps.

The designation of the Celanese resin is 30 - 129. Property data for the E-glass/epoxy composite selected is given in Table 5-1, while data for the T2014-T6 aluminum alloy used in the existing roadwheel design is in Table 5-2.

5.1.5. Insert Design and Bonding. Composite materials are subject to creep under contact (bearing) stress leading to loss of tension in threaded fasteners. This can be overcome by using metallic inserts around fastener holes. 7076-T651 aluminum alloy has been selected as the insert material because it combines low density, relatively good corrosion resistance, and high strength.

The inserts will be retained in the composite material by a combination of threads cut directly into the composite, and a flexible urethane adhesive (Furane "Urethane" 5757A/B). This system has proved satisfactory on vehicle tests of a composite Roadwheel.

5.2. Stress Analysis

5.2.1. Description of Technique. Stress analysis of the composite roadwheel was performed with a 3-dimensional model prepared using the NASTRAN finite-element computer model. Anlaysis proceeded in four stages:

(a) NASTRAN analysis of initial composite design.

(b) NASTRAN analysis of existing aluminum design.

(c) Load testing of aluminum wheel to validate NASTRAN modeling.

(d) NASTRAN analysis of revised composite design.

TABLE 5-1

E-GLASS/CELANESE 30-129

LONGITUDINAL MODULUS (E11) = 6500000 psi (44816 MPa)
TRANSVERSE MODULUS (E22) = 1000000 psi (6895 MPa)
NORMAL MODULUS (E33) = 1000000 psi (6895 MPa)
INPLANE SHEAR MODULUS (G12) = 600000 psi (4137 MPa)
LONGITUDINAL NORMAL SHEAR MODULUS (G13) = 600000 psi (4137 MPa)
TRANSVERSE NORMAL SHEAR MODULUS (G23 = 600000 psi (4137 MPa)
POISSON'S RATIO (Nu12) = 0.27
POISSON'S RATIO (Nu23) = 0.3
LONGITUDINAL TENSILE STRENGTH = 160000 psi (1103.2 MPa)
LONGITUDINAL COMPRESSIVE STRENGTH = 180000 psi (1241 MPa)
TRANSVERSE TENSILE STRENGTH = 7000 psi (48.26 MPa)
TRANSVERSE COMPRESSIVE STRENGTH = 15000 psi (103.42 MPa)
NORMAL TENSILE STRENGTH = 7000 psi (48.26 MPa)
NORMAL COMPRESSIVE STRENGTH = 15000 psi (103.42 MPa)
INPLANE SHEAR STRENGTH = 10000 (68.95 MPa)
LONGITUDINAL NORMAL SHEAR STRENGTH = 10000 (68.95 MPa)
TRANSVERSE NORMAL SHEAR STRENGTH = 10000 (68.95 MPa)

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TABLE 5-2

ALUMINUM ALLOY 2014-T6

LONGITUDINAL MODULUS (E11) = 1.05E+7 (10.5 X 10^6 psi or 72395 MPa)
TRANSVERSE MODULUS (E22) = 1.05E+7 (10.5 X 10^6 psi or 72395 MPa)
NORMAL MODULUS (E33) = 1.05E+7 (10.5 X 10^6 psi or 72395 MPa)
INPLANE SHEAR MODULUS (G12) = 3900000 psi (26890 MPa)
LOGITUDINAL NORMAL SHEAR MODULUS (G13) = 3900000 psi (26890 MPa)
TRANSVERSE NORMAL SHEAR MODULUS (G23) = 3900000 psi (26890 MPa)
POISSON'S RATIO (Nu12) = 0.3
POISSON'S RATIO (Nu23) = 0.3
LOGITUDINAL TENSILE STRENGTH = 60000 psi (413.68 MPa)
LOGITUDINAL COMPRESSIVE STRENGTH = 60000 psi (413.68 MPa)
TRANSVERSE TENSILE STRENGTH = 60000 psi (413.68 MPa)
TRANSVERSE COMPRESSIVE STRENGTH = 60000 psi (413.68 MPa)
NORMAL TENSILE STRENGTH = 60000 psi (413.68 MPa)
NORMAL COMPRESSIVE STRENGTH = 60000 psi (413.68 MPa)
INPLANE SHEAR STRENGTH = 42000 psi (289.6 MPa)
LOGITUDINAL NORMAL SHEAR STRENGTH = 42000 psi (289.6 MPa)
TRANSVERSE NORMAL SHEAR STRENGTH = 42000 psi (289.6 MPa)

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The roadwheel was modeled using approximately 1,500 CHEXA and CPENTA solid elements. Essentially similar techniques were used for both the aluminum and composite wheels. In each case, the model was subjected to a radial load of 79,000 (351.4 kN) lbs, the maximum value quoted in Attachment II of the contract.
Because the NASTRAN analysis was exclusively elastic, it is possible to predict the stresses resulting from lower or higher load levels from the results of the analysis. The defined loading conditions permitted the analysis of a symetrical half model (See Figures 5-5 to 5-8).

For the aluminum model, the wheel geometry was based on TACOM Drawing No. 12274482, and material properties were as shown in Table 5-2. Geometry of the initial composite design was based on Compositek Drawing No. CX-00090 (Figure 5-3), and No. CX-00098 (Figure 5-4). For a composite material, mechanical properties vary as a function of fiber orientation. This effect was allowed for in the NASTRAN model by using varying material properties depending on the radial position of the element considered. Composite material properties were computed from the basic data of Table 5-1 using an in-house computer program. The variation of modulus with fiber angles is shown in Figure 5-9.

The conditions of loading and restraint of a rubber-tired wheel are relatively difficult to simulate, since application of a fixed load at the rim will negate the load-sharing effect of the tire. For both NASTRAN produced-models, the required vertical load was applied at the center mounting points, and the tire was simulated by a number of constant-volume, low-stiffness elements between the wheel rim and a fixed plane. The restraint effect of the vehicle mounting flange at the wheel hub was partially simulated by constraining all mounting bolt positions to move together vertically.

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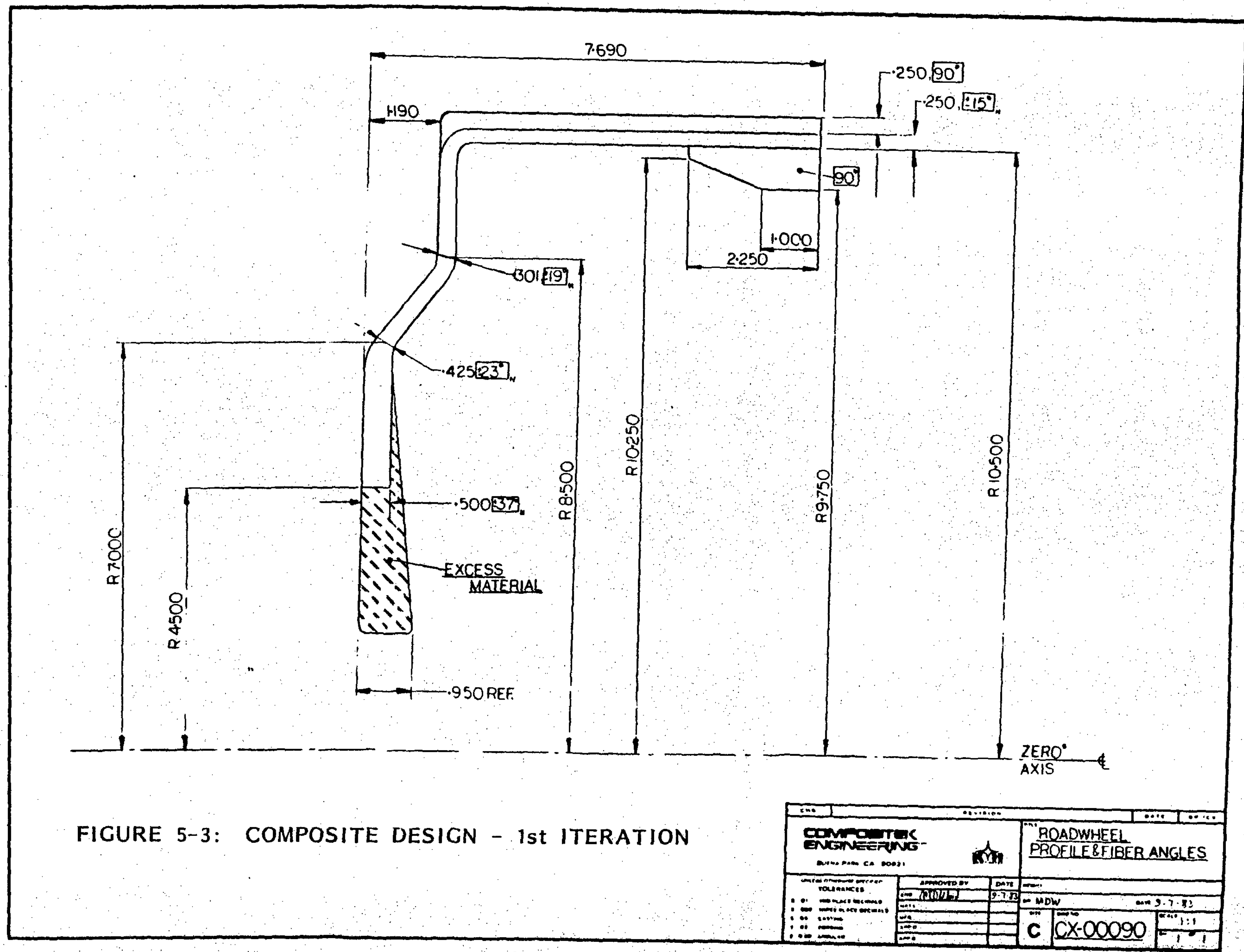

FIGURE 5-3: COMPOSITE DESIGN - 1st ITERATION

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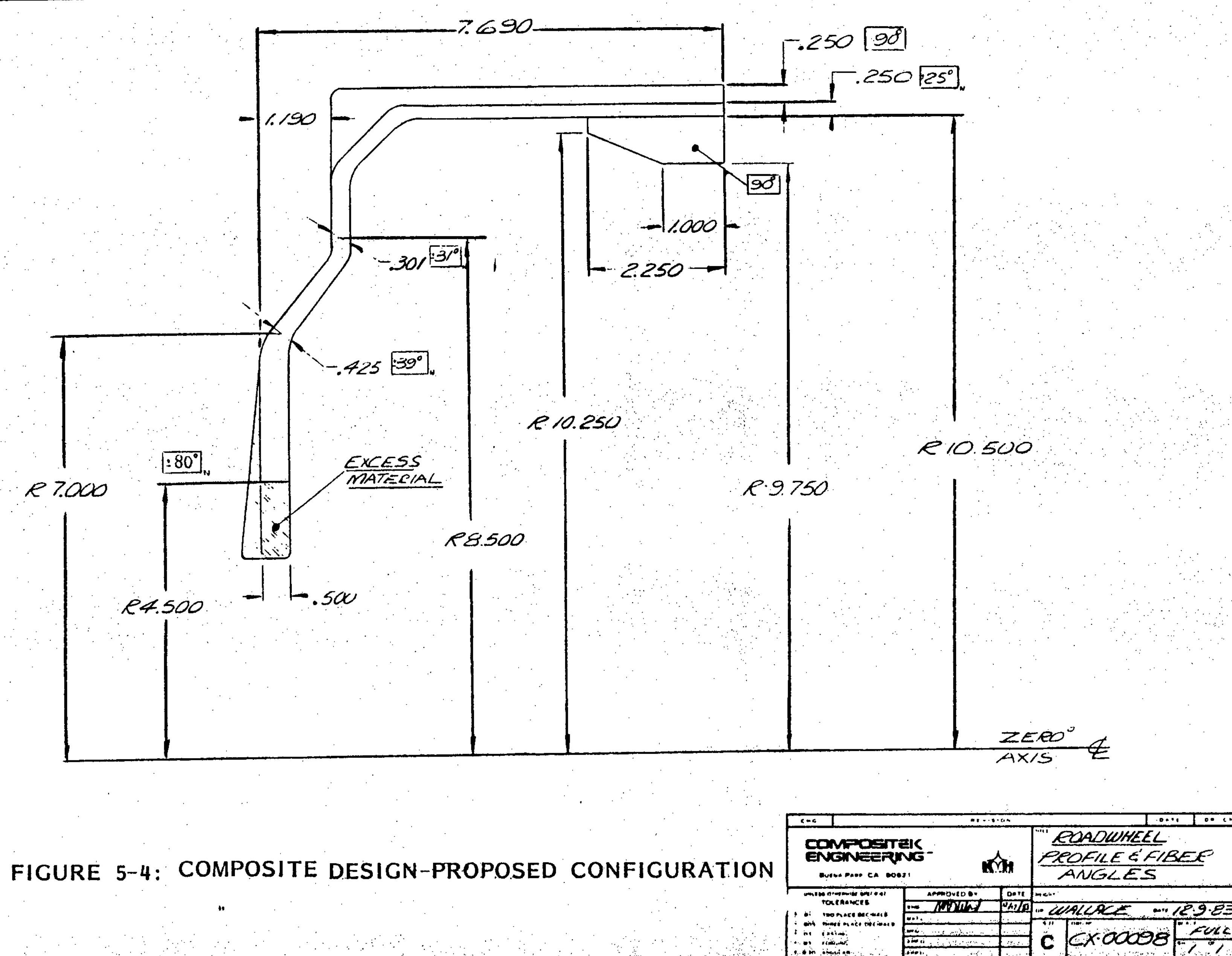

FIGURE 5-4: COMPOSITE DESIGN-PROPOSED CONFIGURATION

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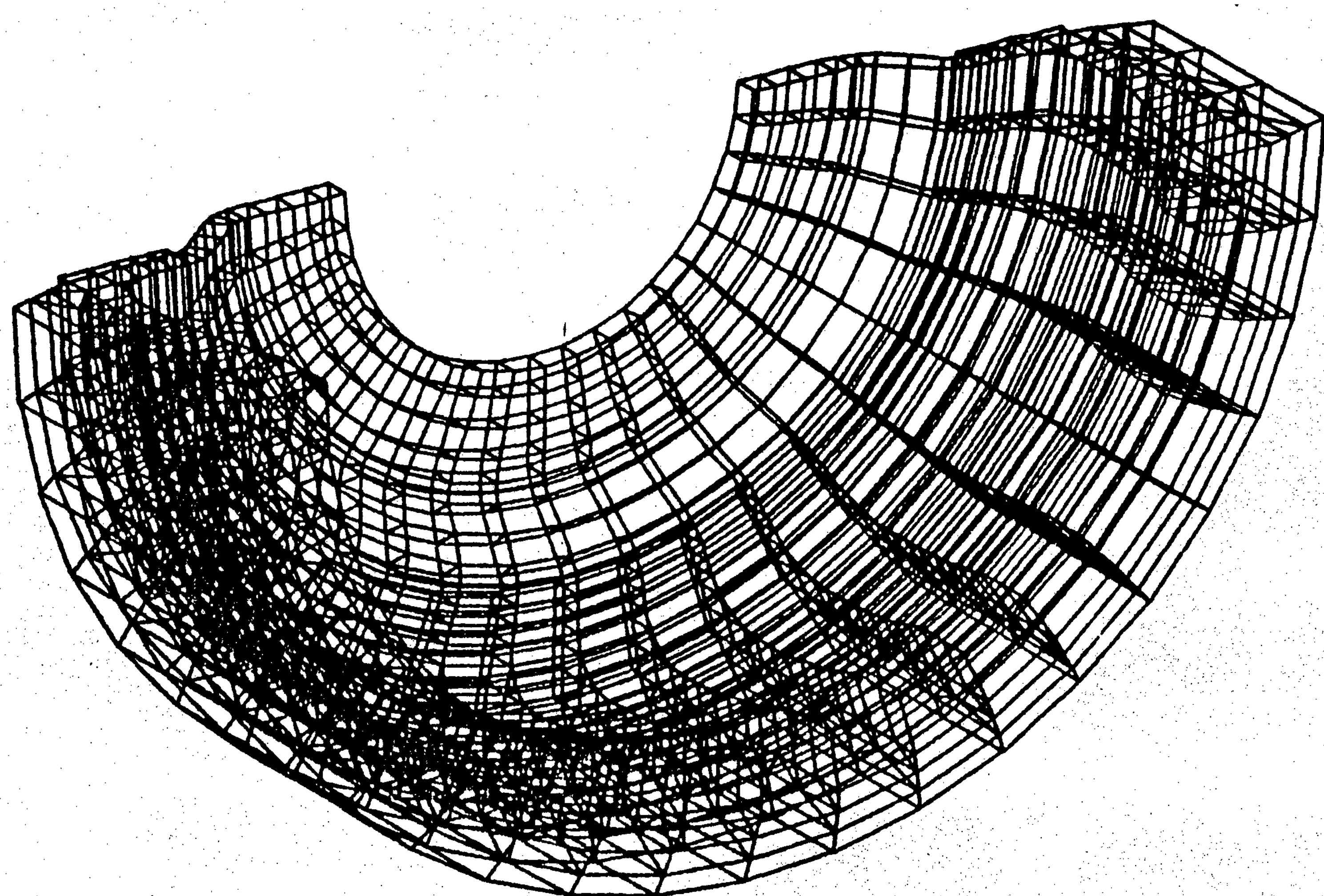

FIGURE 5-5 ALUMINUM ARMY TANK WHEEL ANALYSIS MODEL
ALUMINUM BASELINE TANK WHEEL, INTEGRAL WEAR PLATE

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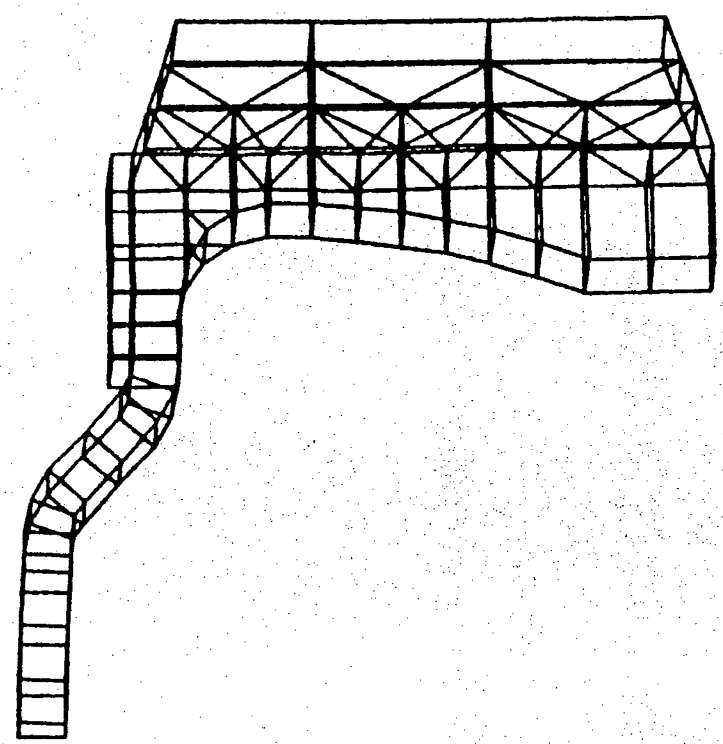

FIGURE 5-6: ALUMINUM ARMY TANK WHEEL ANALYSIS MODEL
ALUMINUM BASELINE TANK WHEEL, INTEGRAL WEAR PLATE
158,000 LB IMPACT LOADING
STATIC DEFOR. SUBCASE 1 LOAD 101

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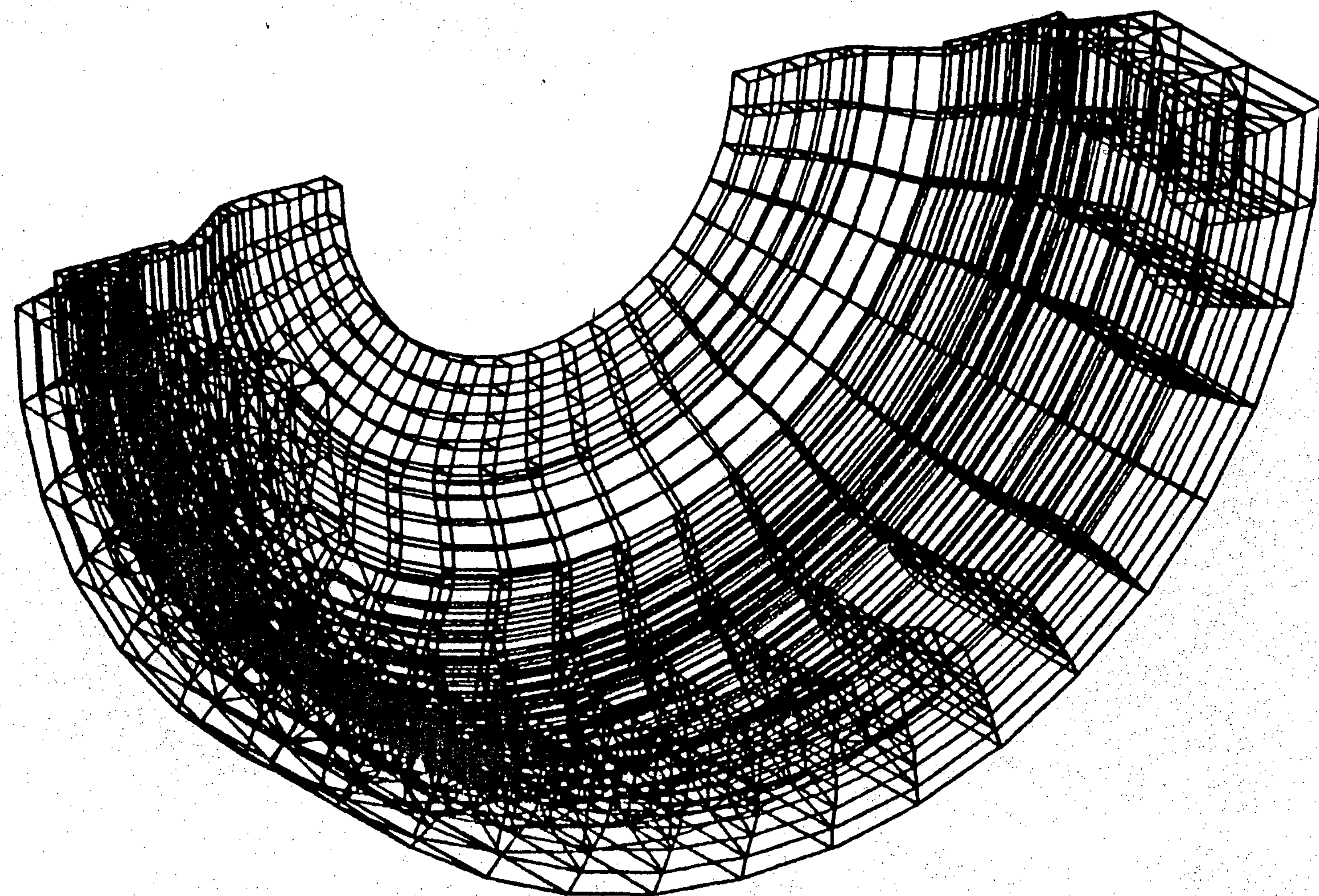

FIGURE 5-7: COMPOSITE ARMY TANK WHEEL ANALYSIS MODEL
SECOND GENERATION GLASS/EPOXY TANK WHEEL

UNDEFORMED SHAPE

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SEGMENT 81-90 DEGREES 4 MAX-DEF. = 1.37598510

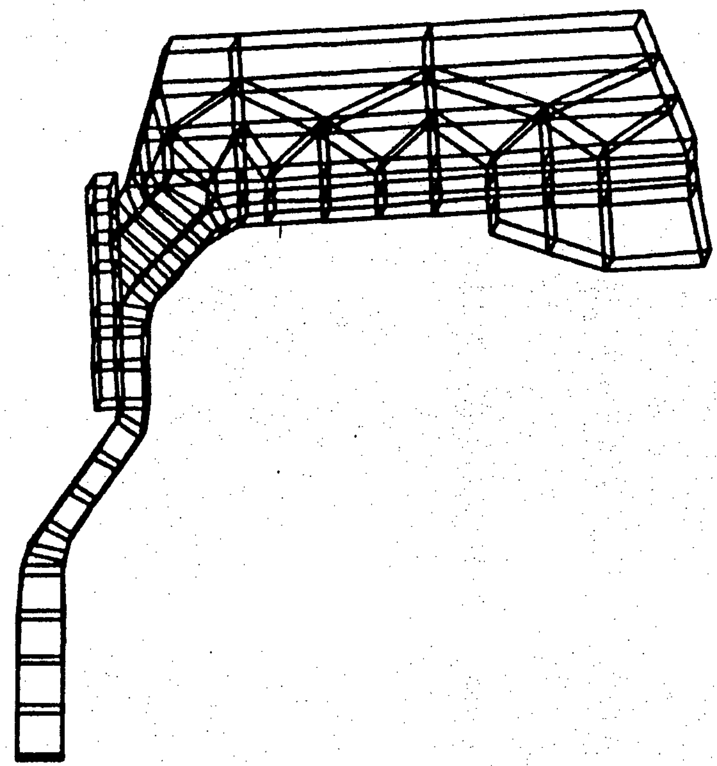

FIGURE 5-8: COMPOSITE ARMY TANK WHEEL ANALYSIS MODEL
SECOND GENERATION GLASS/EPOXY TANK WHEEL
158,000 LB IMPACT LOADING
STATIC DEFOR. SUBCASE 1 LOAD 101

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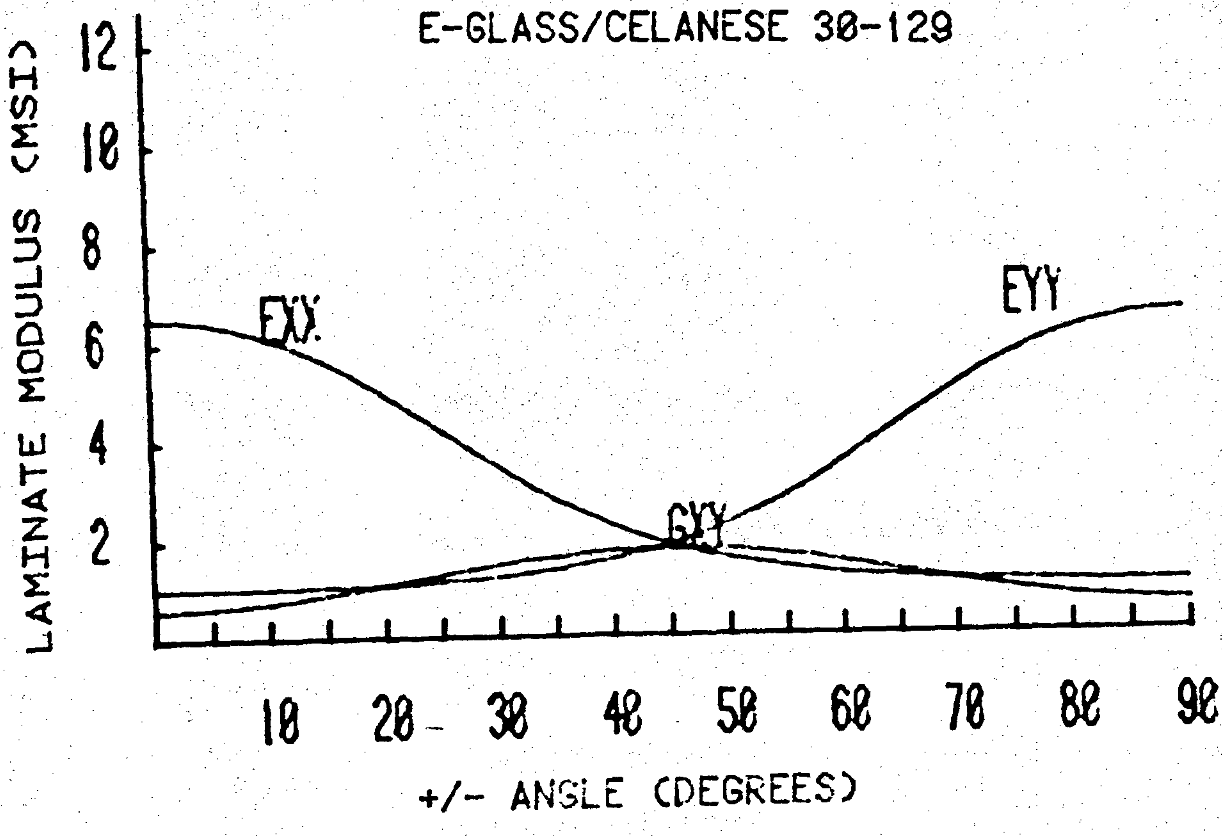

FIGURE 5-9: VARIATION OF PROPERTIES WITH FIBER ANGLE

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5.2.2. Stress Data

5.2.2.1 Evaluation. Because of the large number of elements in the NASTRAN models, a large quantity of stress data was generated. Preliminary inspection of data, however, showed that by far the largest stresses were generated along the section of wheel vertically below the hub (i.e., on the load-path between hub and ground). So detailed evaluation of the stress data has concentrated on this area. The convention used to identify points on the cross-section at which stresses are tabulated is shown in Figure 5-10.

5.2.2.2. Aluminum wheel. The NASTRAN-predicted radial and hoop stresses for the aluminum roadwheel are tabulated in Table 5-2. It can be seen that the hoop stresses are low, consistent with Poisson effects in an isotropic material under generally-radial loading. In the radial direction locations 0 through 6 reflect stress distribution in the rim as the rim deflects across its width. The peak predicted radial stress in this area is approximately 85 ksi. (586 MPa) under a radial load of 79,000 lbs. (351.4 kN) locations 7 through 11 reflect the stress due to bending at the rim/disk interface, and the peak value predicted in this area is -61.5 ksi. (-424 MPa) the very high peaks of -108.5 (-748 MPa) and 132 ksi (910 MPa), respectively, represent stresses due to bending in the corners of the angled sections of the disk. The minor peak, to -42.5 kis. (-293 MPa) represents a predicted stress around the hub bolts.

5.2.2.3. Validation. A load test of an aluminum wheel supplied to Compositek by General Dynamics Land Systems Division suggested that NASTRAN-predicted radial stresses were somewhat conservative, probably due to the strictly linear-elastic nature of the NASTRAN analysis. The results of these tests are contained in Compositek Report No. 84-0100. In essence, it is concluded that the NASTRAN stresses should be reduced by a factor of 0.53 to more accurately reflect the stresses seen by the wheel. A second conclusion is that the restraint provided by the mounting flange in the hub area is considerably better than that modeled, reducing the wheel stresses in that area to negligible levels. The revised stresses are reduced to 140 ksi (965.2 MPa) in the disk area.

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TABLE 5-3

NASTRAN-PREDICTED STRESSES IN ALUMINUM ROADWHEEL

(UNDER RADIAL LOAD OF 79,000 LBS. (351.4 kN))

LOCATION	HOOP STRESS (KSI)	(MPa)	RADIAL STRESS (KSI)	(MPa)
0	0	0.	0	0.
1	-2.5	-17.25	9.5	65.5
2	-7.5	-51.7	28.5	196.5
3	-15	-103.4	52	358.55
4	-2.5	-17.25	85	586.05
5	-15	-103.4	85	586.05
6	-2.5	-17.25	37.5	258.55
7	0	0	-37.5	-258.55
8	-7.5	-51.7	-61.5	-424.05
9	-5	-34.45	-4.5	-31.05
10	-5	-34.45	4.5	31.05
11	0	0	4.5	31.05
12	-15	-103.4	-108.5	-748.1
13	10	68.95	-42.5	-293.05
14	22.5	155.15	132	910.1
15	15	103.4	4.5	31.05
16	-7.5	-51.7	-42.5	-293.05
17	2.5	17.25	4.5	31.05

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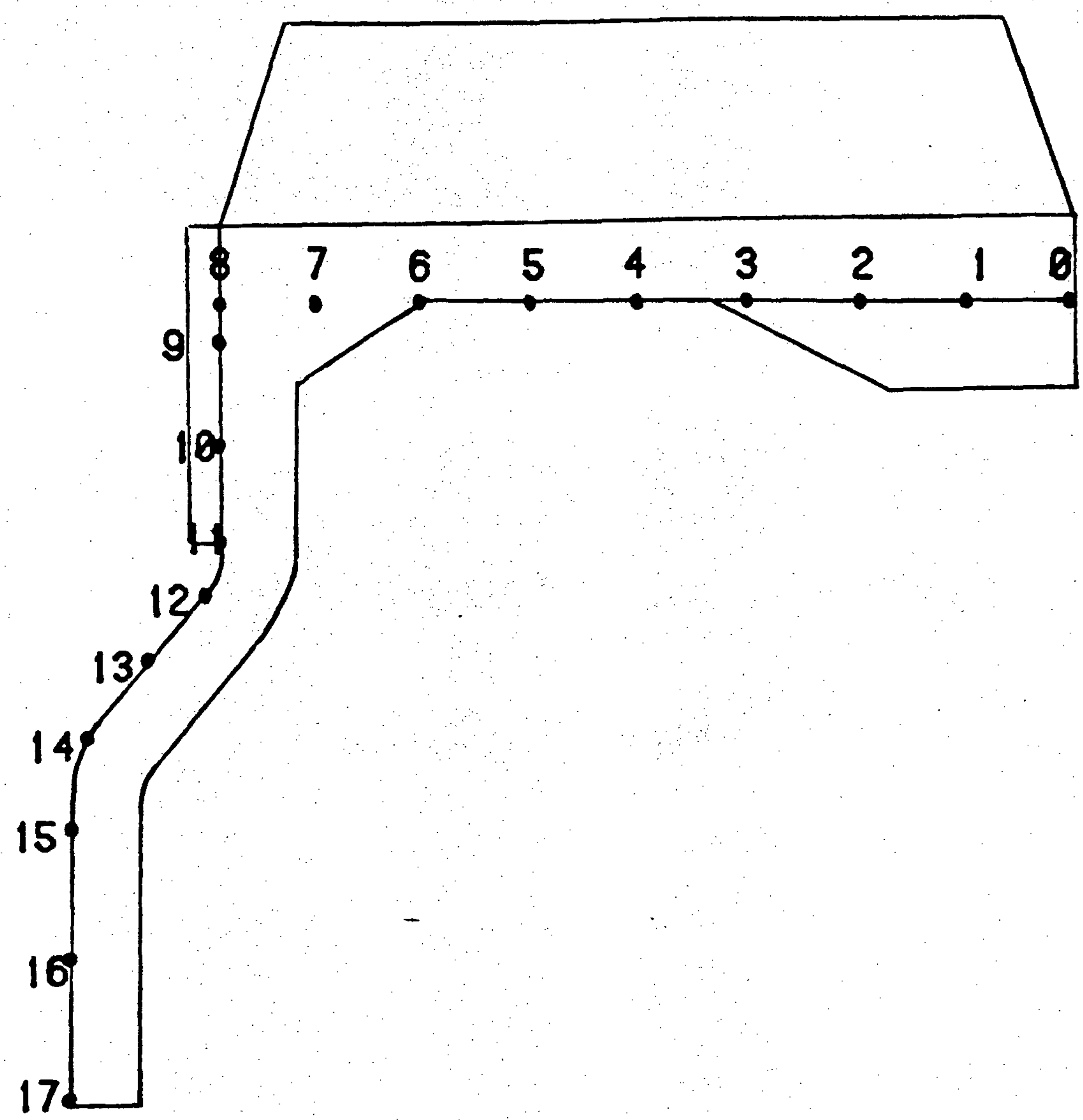

FIGURE 5-10: IDENTIFICATION OF STRESS LOCATIONS

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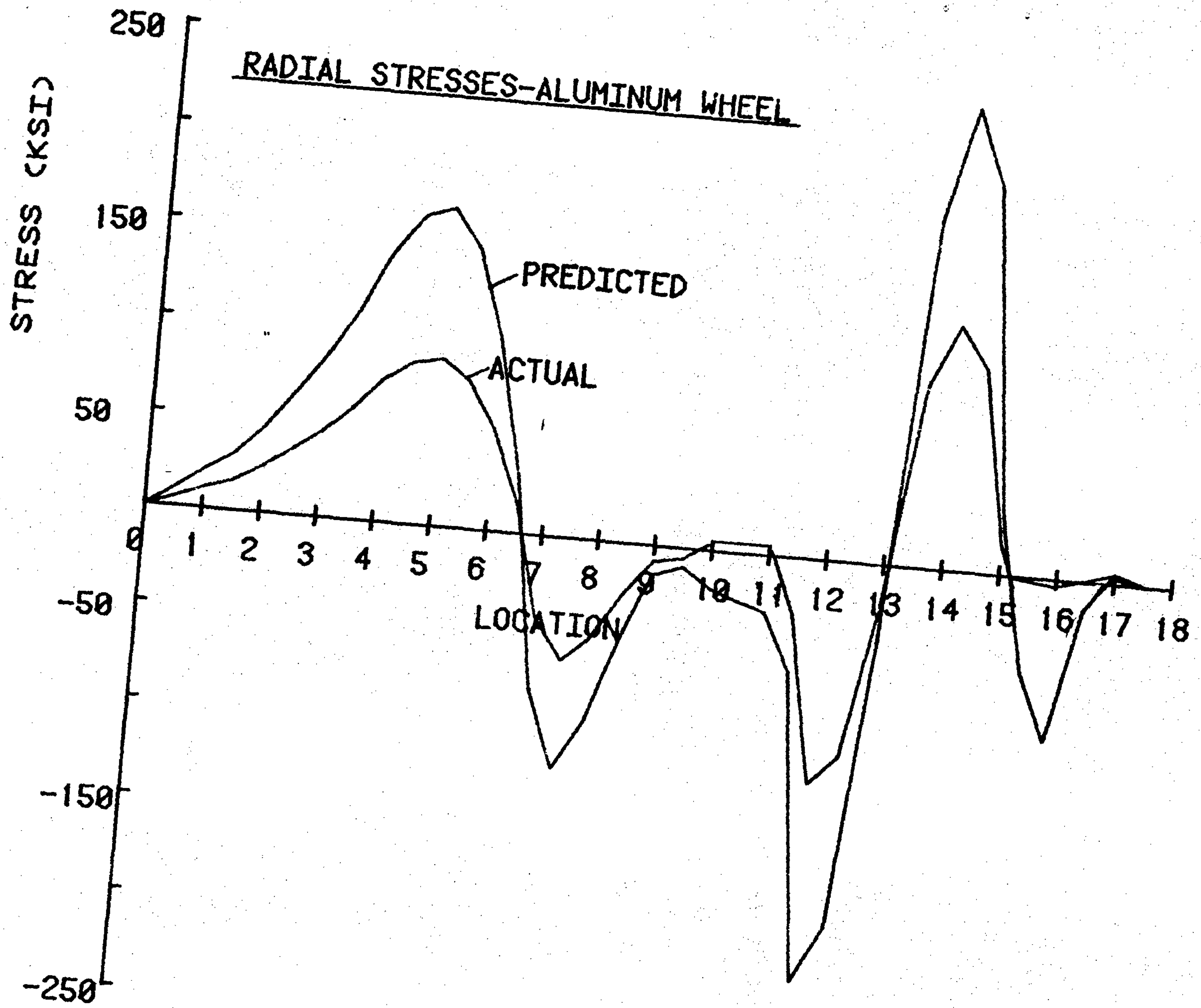
RADIAL STRESSES-ALUMINUM WHEEL
STRESS (KSI)
250
150
50
0
-50
-150
-250
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
LOCATION
PREDICTED
ACTUAL

FIGURE 5-11

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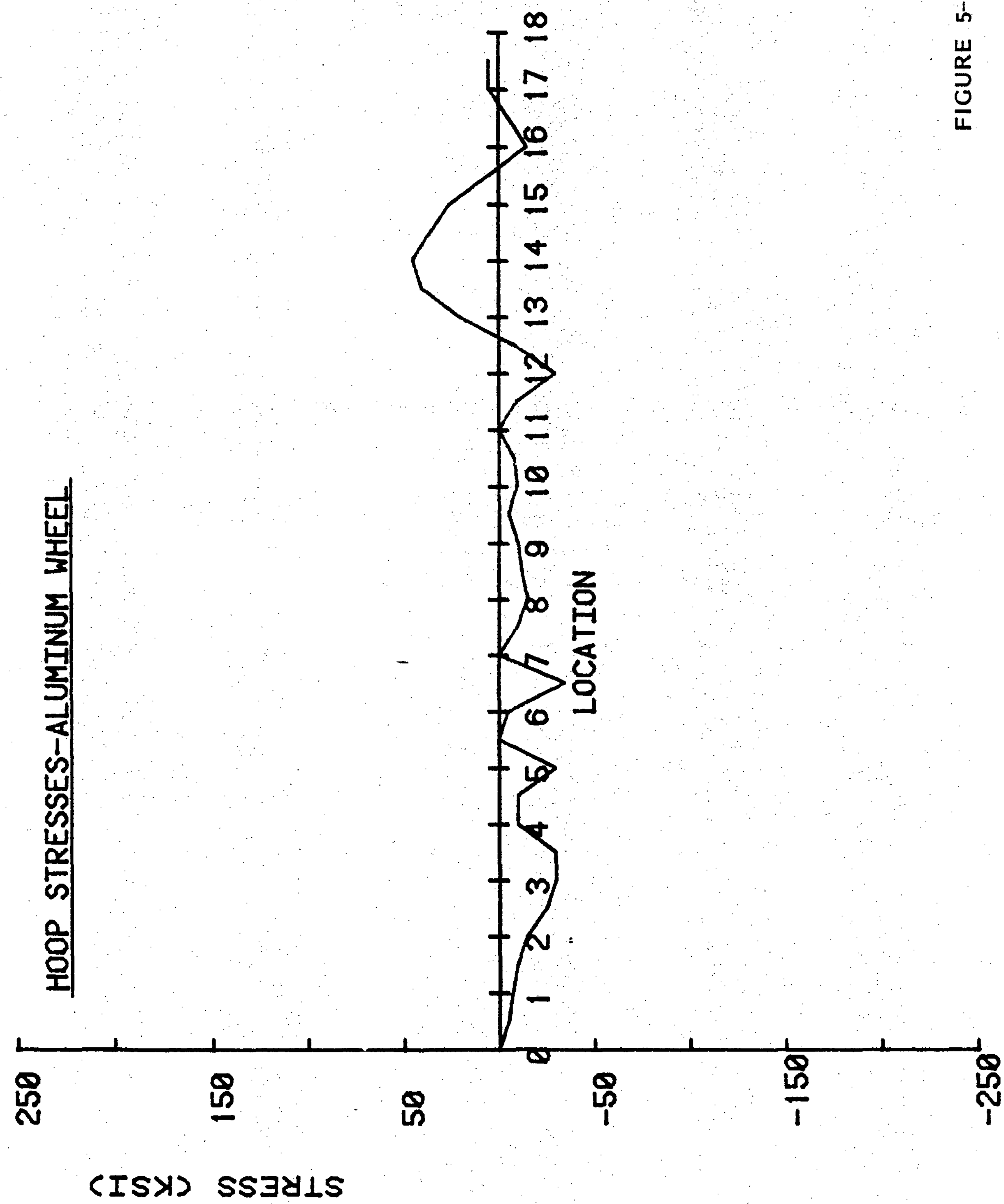
HOOP STRESSES-ALUMINUM WHEEL
STRESS (KSI)
250
150
50
-50
-150
-250
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
LOCATION

FIGURE 5-12

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5.2.2.4. Composite Wheel. The pattern of stresses in the revised composite roadwheel (See Table 5-4 and Figures 5-13 & 5-14) show a pattern similar to the aluminum wheel in the disk area. The radial stress peaks at the corners of the angled section of the disk, due to bending. The peak values are -75 ksi (-517 MPa) and +80 ksi (551.6 MPa). In the rim area, stresses in the composite wheel are distributed differently than in the aluminum wheel, because the circumferential (hoop) fibers pick up most of the load. The peak stress in this region in the composite wheel is -85 ksi (-586 MPa).

5.2.2.5. Factors of Safety. A direct comparison of stress levels in the aluminum and composite wheels is misleading because of differences in material properties. Aluminum is an isotropic material, while fiber-reinforced composites are orthotropic. Aluminum and E-glass reinforced epoxy resin also have different allowable stress characteristics. The factor of safety is obtained by dividing the allowable stress by the actual stress. This procedure is straightforward for the aluminum wheel, as the allowable stress is constant. This study uses the yield stress for aluminum alloy 2014-76 given in MIL-HDBK-5A, which is 60 ksi. (413.7 MPa). To obtain allowable stress levels for the composite material at various orientations, the unindirectional material data form Table 5-1 was processed using an in-house computer program. Both radial and transverse allowable stresses were calculated. The allowable stress value giving the lower factor of safety was used at each location for comparison with the aluminum data. In every case, radial stresses generated the lower factors.

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TABLE 5-4

NASTRAN-PREDICTED STRESSES IN REVISED COMPOSITE ROADWHEEL

(UNDER RADIAL LOAD OF 79,000 LBS. (351.4 kN))

LOCATION	HOOP STRESS (KSI)	HOOP STRESS (MPa)	RADIAL STRESS (KSI)	RADIAL STRESS (MPa)
0	-20	-137.9	-10	-68.95
1	-32.5	224.1	-7.5	-51.7
2	-35	241.3	-7.5	-51.7
3	-32.5	224.1	-2.5	-17.25
4	-42.5	-293.0	-5	-34.45
5	-32.5	-224.1	-15	-103.4
6	-40	-275.8	-15	-103.4
7	-32.5	-224.1	-22.5	-155.15
8	-15	-103.4	-15	-103.4
9	-5	-34.45	-10	-68.95
10	0	0	-5	-34.45
11	0	0	-5	-34.45
12	5	34.47	-37.5	-258.55
13	2.5	17.25	-17.5	-120.65
14	35	241.3	37.5	258.55
15	40	275.8	40	275.8
16	35	241.3	27.5	189.6
17	22.5	155.15	2.5	17.25

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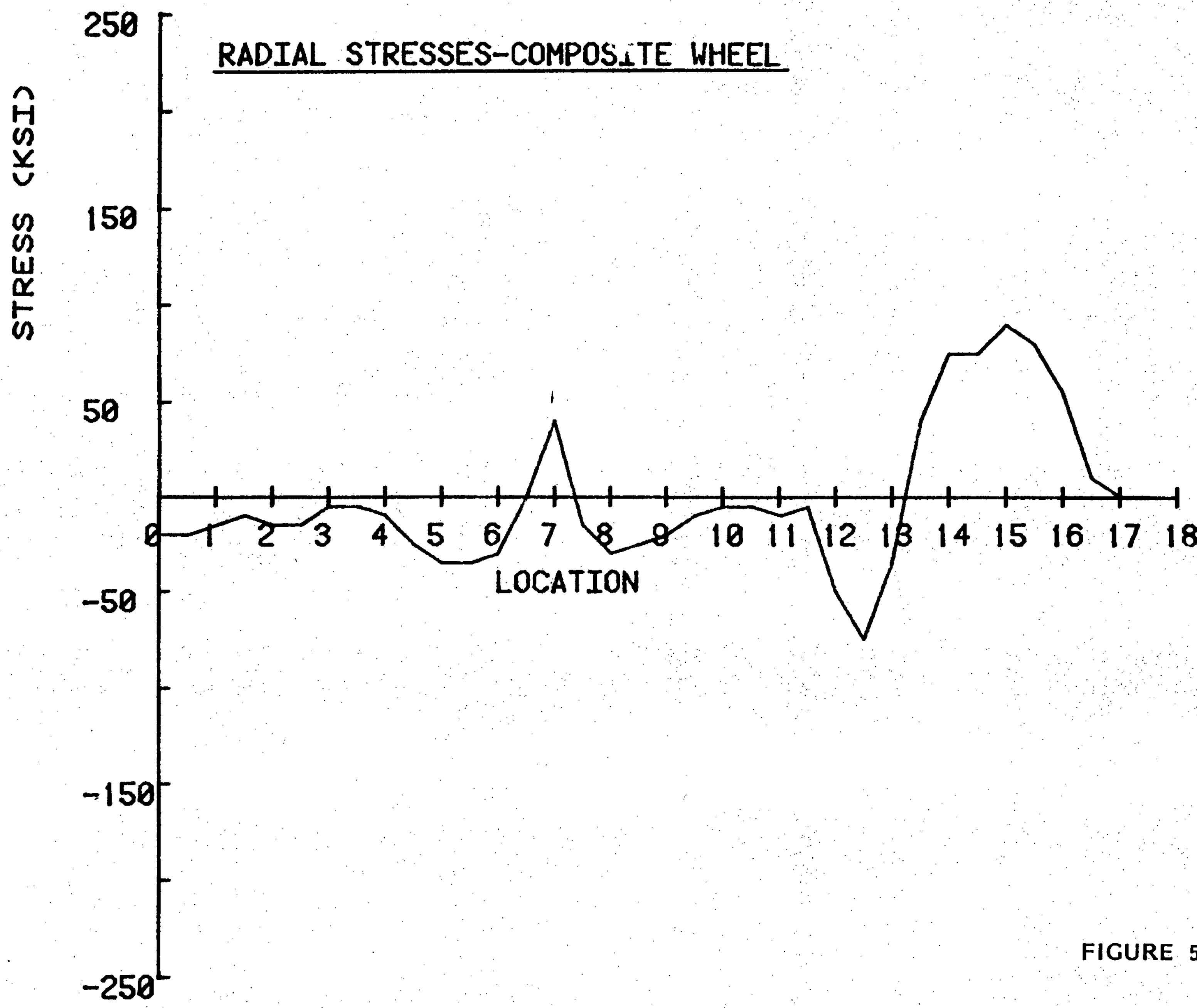
RADIAL STRESSES-COMPOSITE WHEEL
STRESS (KSI)
250
150
50
-50
-150
-250
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
LOCATION

FIGURE 5-13

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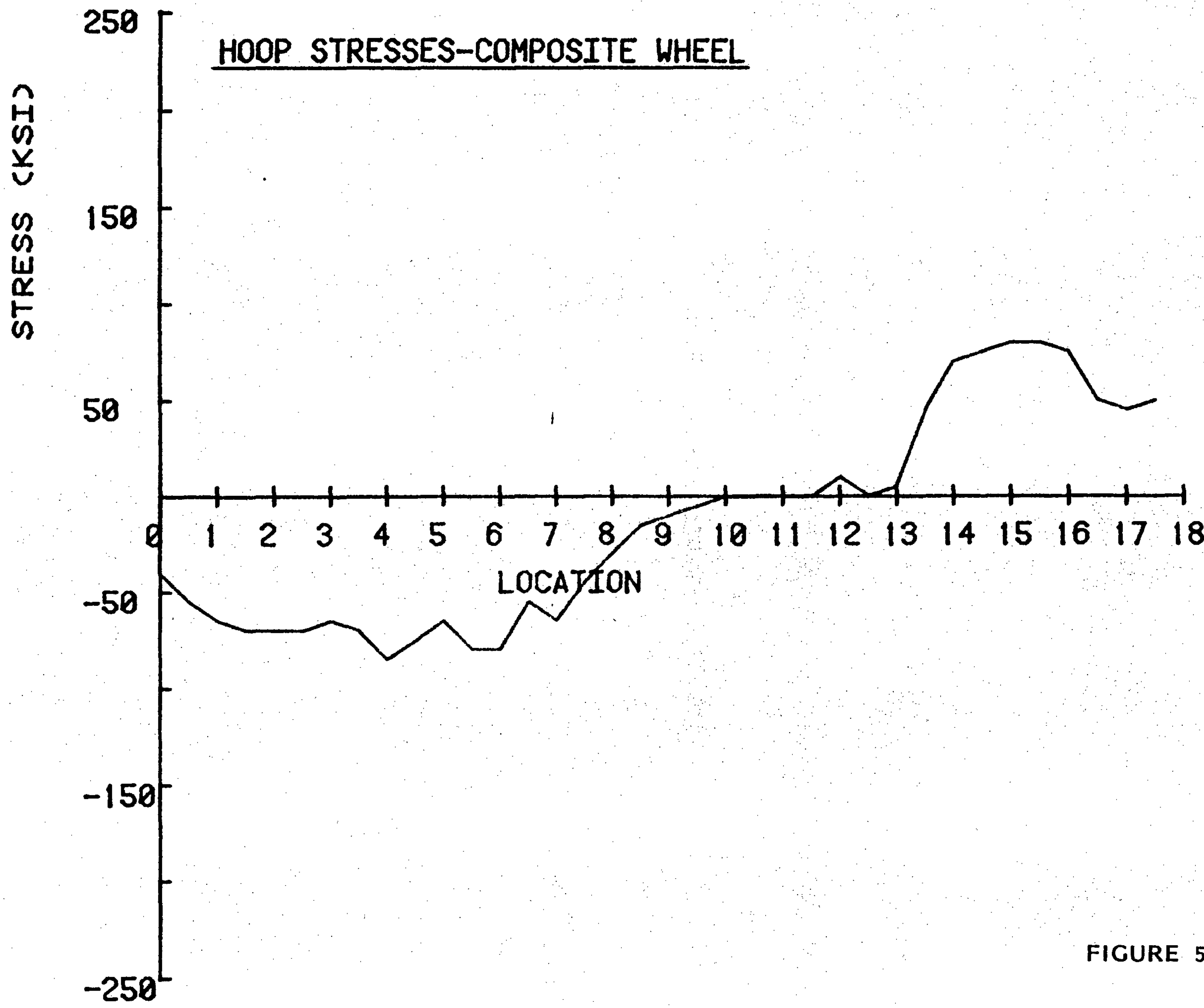
HOOP STRESSES-COMPOSITE WHEEL
STRESS (KSI)
250
150
50
-50
-150
-250
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
LOCATION

FIGURE 5-14

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Table 5-5 shows the calculated and allowable stresses, and factors of safety for the aluminum and composite wheels. While the aluminum stresses have been reduced in line with the results of the validation tests, the composite stresses are left unchanged. This is almost certainly conservative, since it is likely that similar non-linear effects to those occurring in the aluminum wheel will reduce the stress peaks in the composite wheel. The factors of safety are illustrated in Figures 5-15 to 5-17.

In Figure 5-17, the factors of safety for both wheels are shown for comparison. With the aluminum wheel, there are two sets, where the factor-of-safety falls below 1. These areas are between locations 3 and 6, in the rim area, and between locations 11 and 15, in the corners of the angled section of the disk. The global minimum factor-of-safety is 0.860 under a radial loading of 79,000 lbs (351.4 kN). To restore the factor-of-safety to 1, the allowable radial load must be reduced to 68,000 lbs. (302.5 kN)

From Figure 5-17, it can be seen that the composite wheel generally has higher factors of safety than the aluminum wheel throughout the rim area, with the composite safety factor in this area exceeding 1. In the angled section of the disk, the composite wheel has very

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TABLE 5-5

COMPARISON OF RADIAL STRESSES AND FACTORS-OF-SAFETY

(UNDER RADIAL LOAD OF 79,000 LBS.)

	ALUMINUM WHEEL (FACTORED)					COMPOSITE WHEEL (UNFACTORED)				
LOCATION	RADIAL STRESS (KSI)	(MPa)	ALLOWABLE STRESS (KSI)	(MPa)	FACTOR OF SAFETY	RADIAL STRESS (KSI)	(MPa)	ALLOWABLE STRESS (KSI)	(MPa)	FACTOR OF SAFETY
0	0	0	±60	±413.7	24.00	-20	-137.9	-53	-365.4	2.66
1	5	34.45	±60		12.00	-15	-103.4	-53	-365.4	3.55
2	15	103.4	±60		4.00	-15	-103.4	-53	-365.4	3.55
3	27.5	189.6	±60		2.18	-5	-34.5	-53	-365.4	10.64
4	45	310.25	±60		1.74	-10	-68.9	-53	-365.4	5.32
5	45	310.25	±60		1.34	-30	-206.8	-53	-365.4	1.77
6	20	137.9	±60		3.0	-30	-206.8	-53	-365.4	1.77
7	-20	-137.9	±60		3.0	45	310.3	53	+365.4	1.18
8	-32.5	-224.1	±60		1.84	-30	-206.8	-53	-365.4	1.77
9	-2.5	-17.25	±60		24.00	-20	-137.9	-53	-365.4	2.66
10	2.5	17.25	±60		24.00	-10	-68.9	-43	-296.5	4.33
11	2.5	17.25	±60		24.00	-10	-68.9	-43	-296.5	4.33
12	57.5	396.45	±60		1.04	-75	-517.1	-43	-296.5	0.57
13	-22.5	-155.15	±60		2.66	-35	-241.3	-29	-199.9	0.83
14	70	482.65	±60		.86	75	517.1	29	+199.9	0.39
15	10	68.95	±60		6.00	80	551.6	13	89.6	0.16
16	-2.5	17.25	±60		24.00	55	379.2	13	89.6	0.23
17	5	34.5	±60		24.00	5	34.5	13	89.6	2.52

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similar factors of safety to the aluminum wheel. The global minimum factor outside the restrained area at the hub is 0.78 under a radial load of 79,000 lbs., which would requrie a radial load of 62,000 lbs. (275.8 kN) to give a factor of 1. Although this load is marginally less than the 68,000 lbs (302.5 kN) allowable load for the aluminum wheel, it will be recollected that the composite wheel stresses are unfactored, while the aluminum stresses have been reduced by the factor of 0.53 to reflect validation test results. If the factor of 0.53 were applied to the composite wheel stresses, the allowable load would be increased to 116,000 lbs., (516 kN) considerably greater than the value for aluminum. It should be mentioned that the composite roadwheel, recently designed and tested by Compositek Engineering under USMC Contract, showed strength in testing exceeding the values predicted by finite-element analysis. The low factors of safety in the inner hub area are considered to be the result of inadequate constraint in the computer model, as discussed for the aluminum wheel in paragraph 5.2.2.3 above, and are disregarded.

5.2.2.6. Little directly relevant fatigue data is available for the glass-epoxy composite material used in the composite roadwheel. However, filament-winding with epoxy resin, combined with high-pressure compression molding, contributes to superior fatigue performance. It is therefore considered reasonable to assume that the composite material will have fatigue behavior at least as good as the aluminum alloy currently used, and that allowable fatigue load for the composite wheel will be the same (33,000 lbs. (146.8 kN) radial).

5.3. Component Testing

The principal requirement for testing the composite roadwheel is to demonstrate that the composite component is a feasible alternative to the aluminum roadwheel, and has equivalent properties. As outlined in paragraphs 5.2.2.5 and 5.2.2.6 above, the aluminum roadwheel is believed to have a maximum allowable radial load of 68,000 lbs., (302.5 kN) and a fatigue allowable radial load of 33,000 lbs., (146.8 kN). It is recommended that these figures be used as test loads for the composite wheel.

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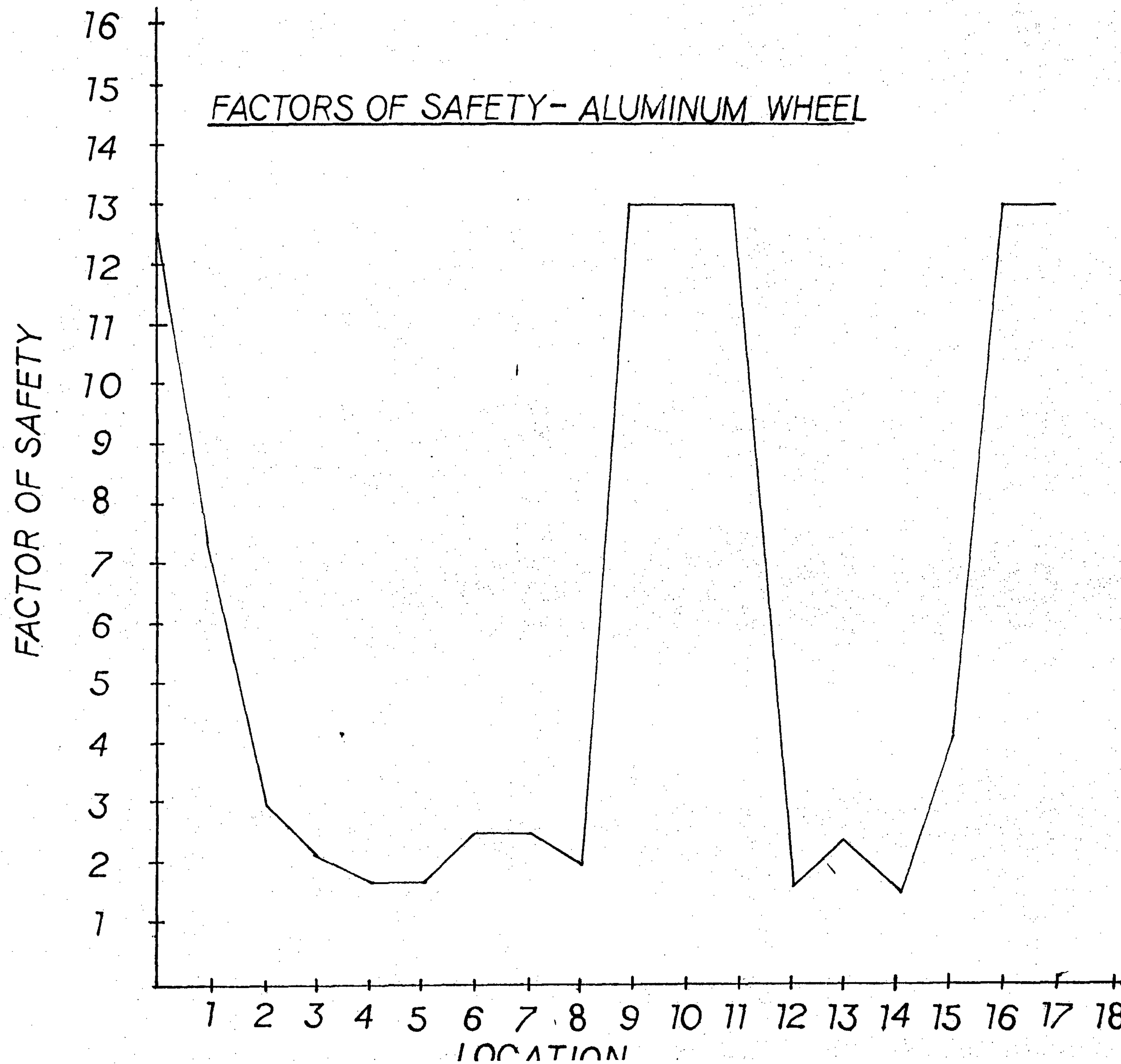
FACTORS OF SAFETY- ALUMINUM WHEEL
FACTOR OF SAFETY
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
LOCATION

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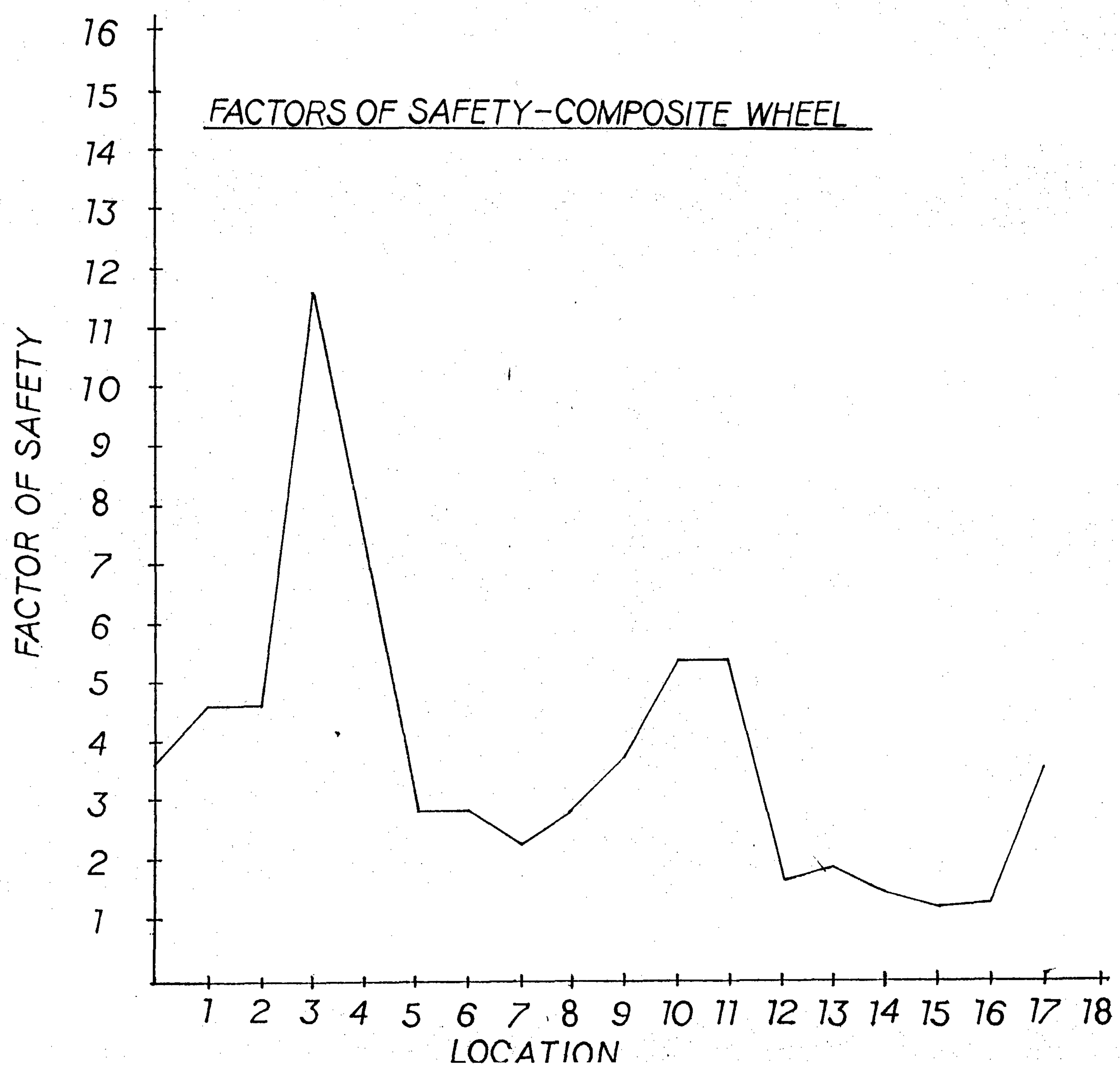

FACTORS OF SAFETY-COMPOSITE WHEEL
FACTOR OF SAFETY
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
LOCATION

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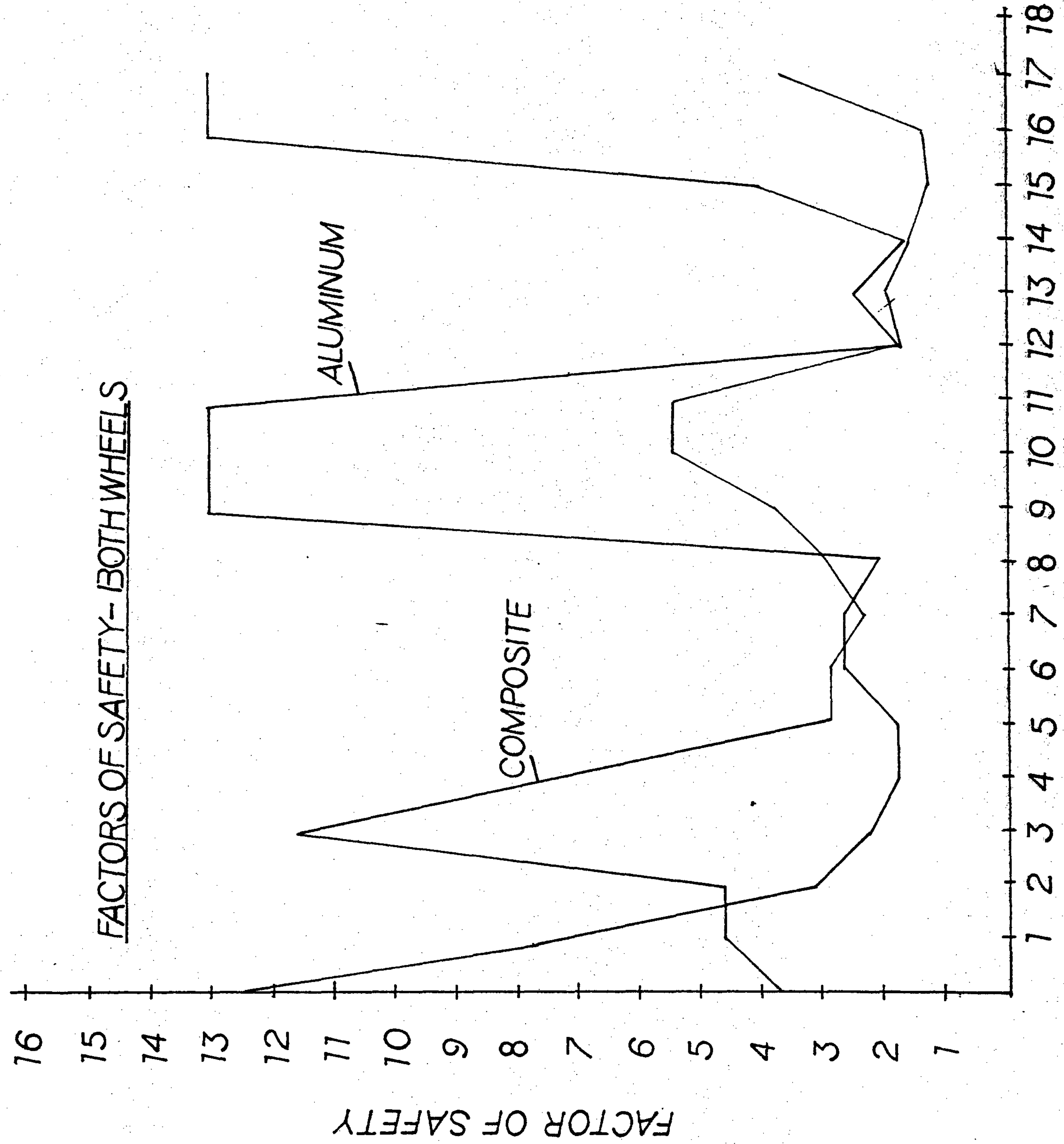
FACTORS OF SAFETY- BOTH WHEELS
ALUMINUM
COMPOSITE
FACTOR OF SAFETY
LOCATION
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16

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DUTY CYCLE

Radial Load, LBS	Radial Loading Ratio minimum/maximum	# Cycles	Lateral Load, LBS
18000	0	40,600	4500
18000	0.2	209,000	4500
18000	0.4	250,000	4500
18000	0.7	132,000	4500
20000	0.4	31,500	5000
22000	0.7	20,000	5500
24000	0.2	211,000	6000
26000	0	76,000	6500
36000	0	44,500	9000
36000	0.2	62,000	9000
45000	0	43,000	0
55000	0	44,500	0
62000	0	12,700	0
80000	0	15,000	0
158000	0	13,000	0

The duty cycle is a conservative estimate of the dynamic loads which the track exerts on one roadwheel station. There are two roadwheels per roadwheel station. The lateral load of the duty cycle is a constant load due to cornering of the vehicle. The radial load is cycled. As an example, a radial load of 18,000 pounds, radial loading ration of 0.2 for 209,000 cycles and a lateral load of 4,500 pounds means that the load imposed on the roadwheel by the track cycles from a maximum of 18,000 pounds to a minimum of 3,600 pounds for 209,000 cycles with a constant lateral load of 4,500 pounds. When determining test procedures, the vehicle's governed maximum speed of 45 miles per hour should be considered.

ADDENDUM: DUTY CYCLE FROM CONTRACT NO. DAAE07-83-R082

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It is proposed that four composite roadwheels, complete with tires vulcanized in place, be subjected to testing. The following test plans are proposed:

5.3.1. Initial Feasibility Testing. Each of the four test wheels should be mounted in a test fixture on the Tinius Olsen load testing machine at Compositek. This machine has a maximum load capacity of 60,000 lbs. (266.9 kN). Using this machine each wheel should be subjected to a radial load of 35,000 lbs. (155.7 kN) at six positions around the circumference, in turn. This will prove the basic structural integrity of the four test items.

5.3.2. Ultimate Load Testing. Two of the test wheels should be allocated for ultimate load testing. Using the same test fixture as was used for initial feasibility testing, but mounted in a test machine of greater load capacity, each of the two wheels should be tested to ultimate radial load. This work should be carried out by Fruehauf Corporation, R&D Division, Detroit, Michigan. Fruehauf Corporation is the parent company of the Kelsey-Hayes Company and Compositek Engineering Corporation.

5.3.3. Fatigue Testing. The remaining two test wheels should be allocated for duty cycle/fatigue testing. A proposed test cycle is shown in Table 5-7. This cycle is based on the duty cycle supplied by TACOM, but with the peak loads adjusted to reflect a more realistic fatigue limit load. Based on initial finite-element modeling, it is not considered that lateral loads have a significant effect on overall stresses. The proposed methods of testing is to use the "bull-wheel" roller-type wheel tester at Fruehauf R&D Division in Detroit. This machine has a maximum radial load capacity of 35,000 lbs. (155.7 kN). Although this machine does have capability for applying lateral loads, this has to be done by running the wheel at an angle to the axis of rotation, giving rise to an unrealistic distribution of load. This procedure is not recommended.

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TABLE 5-7 RECOMMENDED TEST CYCLE (FATIGUE)

RADIAL LOAD (LB)	CYCLES
18,000	632,000
20,000	31,500
22,000	20,000
26,000	211,000
26,000	76,000
33,000	235,000
TOTAL	1,205,500

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